Islamic astronomy by Owen Gingerich.

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Historians who track the development of astronomy from antiquity to the Renaissance sometimes refer to the time from the eighth through the 14th centuries as the Islamic period. During that interval most astronomical activity took place in the Middle East, North Africa and Moorish Spain. While Europe languished in the Dark Ages, the torch of ancient scholarship had passed into Muslim hands. Islamic scholars kept it alight, and from them it passed to Renaissance Europe.

Two circumstances fostered the growth of astronomy in Islamic lands. One was geographic proximity to the world of ancient learning, coupled with a tolerance for scholars of other creeds. In the ninth century most of the Greek scientific texts were translated into Arabic, including Ptolemy's Syntaxis, the apex of ancient astronomy. It was through these translations that the Greek works later became known in medieval Europe. (Indeed, the Syntaxis is still known primarily by its Arabic name, Almagest, meaning "the greatest.")

The second impetus came from Islamic religious observances, which presented a host of problems in mathematical astronomy, mostly related to timekeeping. In solving these problems the Islamic scholars went far beyond the Greek mathematical methods. These developments, notably in the field of trigonometry, provided the essential tools for the creation of Western Renaissance astronomy.

The traces of medieval Islamic astronomy are conspicuous even today. When an astronomer refers to the zenith, to azimuth or to algebra, or when he mentions the stars in the Summer Triangle--Vega, Altair, Deneb--he is using words of Arabic origin. Yet although the story of how Greek astronomy passed to the Arabs is comparatively well known, the history of its transformation by Islamic scholars and subsequent retransmission to the Latin West is only now being written. Thousands of manuscripts remain unexamined. Nevertheless, it is possible to offer at least a fragmentary sketch of the process.

The House of Wisdom

The foundations of Islamic science in general and of astronomy in particular were laid two centuries after the emigration of the prophet Muhammad from Mecca to Medina in A.D. 622. This event, called the Hegira, marks the beginning of the Islamic calendar. The first centuries of Islam were characterized by a rapid and turbulent expansion. Not until the late second century and early third century of the Hegira era was there a sufficiently stable and cosmopolitan atmosphere in which the sciences could flourish. Then the new Abbasid dynasty, which had taken over the caliphate (the leadership of Islam) in 750 and founded Baghdad as the capital in 762, began to sponsor translations of Greek texts. In just a few decades the major scientific works of antiquity--including those of Galen, Aristotle, Euclid, Ptolemy, Archimedes and Apollonius--were translated into Arabic. The work was done by christian and pagan scholars as well as by Muslims.

The most vigorous patron of this effort was Caliph al-Ma'mun, who acceded to power in 813. Al-Ma'mun founded an academy called the House of Wisdom and placed Hunayn ibn Ishaq al-'Ibadi, a Nestorian Christian with an excellent command of Greek, in charge. Hunayn became the most celebrated of all translators of Greek texts. He produced Arabic versions of Plato, Aristotle and their commentators, and he translated the works of the three founders of Greek medicine, Hippocrates, Galen and Dioscorides.

The academy's principal translator of mathematical and astronomical works was a pagan named Thabit ibn Qurra. Thabit was originally a money changer in the marketplace of Harran, a town in northern Mesopotamia that was the center of an astral cult. He stoutly maintained that the adherents of this cult had first farmed the land, built cities and ports and discovered science, but he was tolerated in the Islamic capital. There he wrote more than 100 scientific treatises, including a commentary on the Almagest.

Another mathematical astronomer at the House of Wisdom was al-Khwarizmi, whose Algebra, dedicated to al-Ma'mun, may well have been the first book on the topic in Arabic. Although it was not particularly impressive as a scientific achievement, it did help to introduce Hindu as well as Greek methods into the Islamic world. Sometime after 1100 it was translated into Latin by an Englishman, Robert of Chester, who had gone to Spain to study mathematics. The translation, beginning with the words "Dicit Algoritmi" (hence the modern word algorithm), had a powerful influence on medieval Western algebra.

Moreover, its influence is still felt in all mathematics and science: it marked the introduction into

Europe of "Arabic numerals." Along with certain trigonometric procedures, the Arabs had borrowed from India a system of numbers that included the zero. The Indian numerals existed in two forms in the Islamic world, and it was the Western form that was transmitted through Spain into medieval Europe. These numerals, with the explicit zero, are far more efficient than Roman numerals for making calculations.

Yet another astronomer in ninth-century Baghdad was Ahmad al-Farghani. His most important astronomical work was his Jawami, or Elements, which helped to spread the more elementary and nonmathematical parts of Ptolemy's earth-centered astronomy. The Elements had a considerable influence in the West. It was twice translated into Latin in Toledo, once by John of Seville (Johannes Hispalensis) in the first half of the 12th century, and more completely by Gerard of Cremona a few decades later.

Gerard's translation of al-Farghani provided Dante with his principal knowledge of Ptolemaic astronomy. (In the Divine Comedy the poet ascends through the spheres of the planets, which are centered on the earth.) It was John of Seville's earlier version, however, that became better known in the West. It served as the foundation for the Sphere of Sacrobosco, a still further watered-down account of spherical astronomy written in the early 13th century by John of Holywood (Johannes de Sacrobosco). In universities throughout Western Christendom the Sphere of Sacrobosco became a long-term best seller. In the age of printing it went through more than 200 editions before it was superseded by other textbooks in the early 17th century. With the exception of Euclid's Elements no scientific textbook can claim a longer period of supremacy.

Thus from the House of Wisdom in ancient Baghdad, with its congenial tolerance and its unique blending of cultures, there streamed not only an impressive sequence of translations of Greek scientific and philosophical works but also commentaries and original treatises. By A.D. 900 the foundation had been laid for the full flowering of an international science, with one language--Arabic--as its vehicle.

Religious Impetus

A major impetus for the flowering of astronomy in Islam came from religious observances, which presented an assortment of problems in mathematical astronomy, specifically in spherical geometry.

At the time of Muhammad both Chistians and Jews observed holy days, such as Easter and Passover, whose timing was determined by the phases of the moon. Both communities had confronted the fact that the approximately 29.5-day lunar months are not commensurable with the 365-day solar year: 12 lunar months add up to only 354 days. To solve the problem Christians and Jews had adopted a scheme based on a discovery made in about 430 B.C. by the Athenian astronomer Meton. In the 19-year Metonic cycle there were 12 years of 12 lunar months and seven years of 13 lunar months. The periodic insertion of a 13th month kept calendar dates in step with the seasons.

Apparently, however, not every jurisdiction followed the standard pattern; unscrupulous rulers occasionally added the 13th month when it suited their own interests. To Muhammad this was the work of the devil. In the Koran (chapter 9, verse 36) he decreed that "the number of months in the sight of God is 12 [in a year]--so ordained by Him the day He created the heavens and the earth; of them four are sacred: that is the straight usage." Caliph 'Umar I (634-44) interpreted this decree as requiring a strictly lunar calendar, which to this day is followed in most Islamic countries. Because the Hegira year is about 11 days shorter than the solar year, holidays such as Ramadan, the month of fasting, slowly cycle through the seasons, making their rounds in about 30 solar years.

Furthermore, Ramadan and the other Islamic months do not begin at the astronomical new moon, defined as the time when the moon has the same celestial longitude as the sun and is therefore invisible; instead they begin when the thin crescent moon is first sighted in the western evening sky. Predicting just when the crescent moon would become visible was a special challenge to Islamic mathematical astronomers. Although Ptolemy's theory of the complex lunar motion was tolerably accurate near the time of the new moon, it specified the moon's path only with respect to the ecliptic (the sun's path on the celestial sphere). To predict the first visibility of the moon it was necessary to describe its motion with respect to the horizon, and this problem demanded fairly sophisticated spherical geometry.

Two other religious customs presented problems requiring the application of spherical geometry. One problem, given the requirement for Muslims to pray toward Mecca and to orient their mosques in that direction, was to determine the direction of the holy city from a given location. Another problem was to determine from celestial bodies the proper times for the prayers at sunrise, at midday, in the

afternoon, at sunset and in the evening.

Solving any of these problems involves finding the unknown sides or angles of a triangle on the celestial sphere from the known sides and angles way of finding the time of day, for example, is to construct a triangle whose vertexes are the zenith, the north celestial pole and the sun’s position. The observer must know the altitude of the sun and that of the pole; the former can be observed, and the latter is equal to the observer’s latitude. The time is then given by the angle at the intersection of the meridian (the arc through the zenith and the pole) and the sun’s hour circle (the arc through the sun and the pole).

The method Ptolemy used to solve spherical triangles was a clumsy one devised late in the first century by Menelaus of Alexandria. It involved setting up two intersecting right triangles; by applying the Menelaus theorem it was possible to solve for one of the six sides, but only if the other five sides were known. To tell the time from the sun’s altitude, for instance, repeated applications of the Menelaus theorem were required. For medieval Islamic astronomers there was an obvious challenge to find a simpler trigonometric method.

By the ninth century the six modern trigonometric functions--sine and cosine, tangent and cotangent, secant and cosecant--had been identified, whereas Ptolemy knew only a single chord function. Of the six, five seem to be essentially Arabic in origin; only the sine function was introduced into Islam from India. (The etymology of the word sine is an interesting tale. The Sanskrit word was ardhajya, meaning "half chord," which in Arabic was shortened and transliterated as jyb. In Arabic vowels are not spelled out, and so the word was read as jayb, meaning "pocket" or "gulf." In medieval Europe it was then translated as sinus, the Latin word for gulf.) From the ninth century onward the development of spherical trigonometry was rapid. Islamic astronomers discovered simple trigonometric identities, such as the law of sines, that made solving spherical triangles a much simpler and quicker process.

Stars and Astrolabes

One of the most conspicuous examples of modern astronomy’s Islamic heritage is the names of stars. Betelgeuse, Rigel, Vega, Aldebaran and Fomalhaut are among the names that are directly Arabic in origin or are Arabic translations of Ptolemy’s Greek descriptions.

In the Almagest Ptolemy had provided a catalogue of more than 1,000 stars. The first critical revision of the catalogue was compiled by ’Abd al-Rahman al-Sufi, a 10th-century Persian astronomer who worked in both Iran and Baghdad. Al-Sufi’s Kitab su-war al-kawakib ("Book on the Constellations of Fixed Stars") did not add or subtract stars from the Almagest list, nor did it remeasure their often faulty positions, but it did give improved magnitudes as well as Arabic identifications. The latter were mostly just translations of Ptolemy.

For many years it was assumed that al-Sufi’s Arabic had established the stellar nomenclature in the West. It now seems that his 14th- and 15th-century Latin translators went to a Latin version of the Arabic edition of Ptolemy himself for the star descriptions, which they combined with al-Sufi’s splendid pictorial representations of the constellations. Meanwhile the Arabic star nomenclature trickled into the West by another route: the making of astrolabes.

The astrolabe was a Greek invention. Essentially it is a two-dimensional model of the sky, an analog computer for solving the problems of spherical astronomy [see "The Astrolabe," by J. D. North; SCIENTIFIC AMERICAN, January, 1974]. A typical astrolabe consists of a series of brass plates nested in a brass matrix known in Arabic as the umm (meaning "womb"). The uppermost plate, called the ’ankabut (meaning "spider") or in Latin the rete, is an open network of two or three dozen pointers indicating the position of specific stars. Under the rete are one or more solid plates, each engraved with a celestial coordinate system appropriate for observations at a particular latitude: circles of equal altitude above the horizon (analogous to terrestrial latitude lines) and circles of equal azimuth around the horizon (analogous to longitude lines). By rotating the rete about a central pin, which represents the north celestial pole, the daily motions of the stars on the celestial sphere can be reproduced.

Although the astrolabe was known in antiquity, the earliest dated instrument that has been preserved comes from the Islamic period [see cover of this issue]. It was made by one Nastulus in 315 of the Hegira era (A.D. 927-28), and it is now one of the treasures of the Kuwait National Museum. Only a handful of 10th-century Arabic astrolabes exist, whereas nearly 40 have survived from the 11th and 12th centuries. Several of these were made in Spain in the mid-11th century and have a distinctly Moorish style.

The earliest extant Arabic treatise on the astrolabe was written in Baghdad by one of Caliph al-Ma’mun’s astronomers, ’Ali ibn ’Isa. Later members of the Baghdad school, notably al-Farghani,

also wrote on the astrolabe. Al-Farghani's treatise was impressive for the mathematical way he applied the instrument to problems in astrology, astronomy and timekeeping.

Many of these treatises found their way to Spain, where they were translated into Latin in the 12th and 13th centuries. The most popular work, which exists today in about 200 Latin manuscript copies, was long mistakenly attributed to Masha'allah, a Jewish astronomer of the eighth century who participated in the decision to found Baghdad; it probably is a later pastiche from a variety of sources. In about 1390 this treatise was the basis for an essay on the astrolabe by the English poet Geoffrey Chaucer. Indeed, England seems to have been the gateway for the introduction of the astrolabe from Spain into Western Christendom in the late 13th and 14th centuries. It is possible that scientific activity centered at Oxford at the time contributed to the surge of interest in the device. Merton and Oriel colleges of the University of Oxford still own fine 14th-century astrolabes.

On them one finds typical sets of Arabic star names written in Gothic Latin letters. Included on the Merton College astrolabe, for example, are Arabic names that have evolved into standard modern nomenclature: Wega, Altahir, Algeuze, Rigil, Elfeta, Alferaz and Mirac. Thus as a result of the astrolabe tradition of Eastern Islam, transmitted through Spain to England, most navigational stars today have Arabic names, either indigenous ones or Arabic translations of Ptolemy's Greek descriptions.

Refining Ptolemy

It would be wrong to conclude from the preponderance of Arabic star names that Islamic astronomers made exhaustive studies of the sky. On the contrary, their observations were quite limited. For instance, the spectacular supernova (stellar explosion) of 1054, which produced the Crab Nebula, went virtually unrecorded in Islamic texts even though it was widely noted in China. Modern astronomers struck by this glaring gap often do not realize that Islamic astronomers failed to document most specific astronomical phenomena. They had little incentive to do so. Their astrology, unlike that of the Chinese, depended not so much on unusual heavenly omens as on planetary positions, and these were quite well described by the Ptolemaic procedures.

The planetary models that Ptolemy devised in the second century A.D. had the sun, the moon and the planets moving around the earth. A simple circular orbit, however, could not account for the fact that a planet periodically seems to reverse its direction of motion across the sky. (According to the modern heliocentric viewpoint, this apparent retrograde motion occurs when the earth is passing or being passed by another planet on its way around the sun.) Hence Ptolemy had each planet moving on an epicycle, a rotating circle whose center moved about the earth on a larger circle called the deferent. The epicycle, together with other geometric devices invented by Ptolemy, gave a fairly good first approximation to the apparent motion of the planets. As a great theoretician, Ptolemy must have been fairly confident of the particular geometry of his models, since he never described how he settled on it.

On the other hand, the idea of applying mathematics to a specific numerical description of the physical world was something rather novel for the Hellenistic Greeks, quite different from the pure mathematics of Euclid and Apollonius. In this part of his program Ptolemy must have realized that improved values for the numerical parameters of his models were both desirable and inevitable, and so he gave careful instructions on how to establish the parameters from a limited number of selected observations. The Islamic astronomers learned this lesson all too well. They limited their observations, or at least the few they chose to record, primarily to measurements that could be used for rederiving key parameters. These included the orientation and eccentricity of the solar orbit and the inclination of the ecliptic plane.

An impressive example of an Islamic astronomer working strictly within a Ptolemaic framework but establishing new values for Ptolemy's parameters was Muhammad al-Battani, a younger contemporary of Thabit ibn Qurra. Al-Battani's Zij ("Astronomical Tables") is still admired as one of the most important astronomical works between the time of Ptolemy and that of Copernicus. Among other things, al-Battani was able to establish the position of the solar orbit (equivalent in modern terms to finding the position of the earth's orbit) with better success than Ptolemy had achieved.

Because al-Battani does not describe his observations in detail, it is not clear whether he adopted an observational strategy different from that of Ptolemy. In any case his results were good, and centuries later his parameters for the solar orbit were widely known in Europe. His Zij first made its way to Spain. There it was translated into Latin early in the 12th century and into Castilian a little more than 100 years later. The fact that only a single Arabic manuscript copy survives (in the Escorial Library

near Madrid) suggests that al-Battani's astronomy was not as highly regarded in Islam as it was in Europe, where the advent of printing ensured its survival and in particular made it available to Copernicus and his contemporaries. In De revolutionibus orbium coelestium ("On the Revolutions of the Heavenly Spheres") the Polish astronomer mentions his ninth-century Muslim predecessor no fewer than 23 times.

In contrast, one of the greatest astronomers of medieval Islam, 'Ali ibn 'Abd al-Rahman ibn Yunus, remained completely unknown to European astronomers of the Renaissance. Working in Cairo a century after al-Battani, Ibn Yunus wrote a major astronomical handbook called the Hakimi Zij. Unlike other Arabic astronomers, he prefaced his Zij with a series of more than 100 observations, mostly of eclipses and planetary conjunctions. Although Ibn Yunus' handbook was widely used in Islam, and his timekeeping tables survived in use in Cairo into the 19th century, his work became known in the West less than 200 years ago.

Throughout the entire Islamic period astronomers stayed securely within the geocentric framework. For this one should not criticize them too harshly. Until Galileo's telescopic observations of the phases of Venus in 1610, no observational evidence could be brought against the Ptolemaic system. Even Galileo's observations could not distinguish between the geo-heliocentric system of Tycho Brahe (in which the other planets revolved about the sun but the sun revolved about the earth) and the purely heliocentric system of Copernicus [see "The Galileo Affair," by Owen Gingerich; SCIENTIFIC AMERICAN, August, 1982]. Furthermore, although Islamic astronomers followed Ptolemy's injunction to test his results, they did not limit themselves simply to improving his parameters. The technical details of his models were not immune from criticism. These attacks, however, were invariably launched on philosophical rather than on observational grounds.

Doubting Ptolemy

Ptolemy's models were essentially a mathematical system for predicting the positions of the planets. Yet in the Planetary Hypotheses he did try to fit the models into a cosmological system, the Aristotelian scheme of tightly nested spheres centered on the earth. He placed the nearest point of Mercury's path immediately beyond the most distant point of the moon's path; immediately beyond the farthest excursion of Mercury lay the nearest approach of Venus, and so on through the spheres for the sun, Mars, Jupiter and Saturn.

To reproduce the observed nonuniform motions of the planets, however, Ptolemy adopted two purely geometric devices in addition to the epicycle. First, he placed the deferent circles off-center with respect to the earth. Second, he made the ingenious assumption that the motion of celestial bodies was uniform not around the earth, nor around the centers of their deferents, but instead around a point called the equant that was opposite the earth from the deferent center and at an equal distance. Eccentric deferents and equants did a good job of representing the varying speeds with which planets are seen to move across the sky, but to some minds they were philosophically offensive.

The equant in particular was objectionable to philosophers who thought of planetary spheres as real physical objects, each sphere driven by the one outside it (and the outermost driven by the prime mover), and who wanted to be able to construct a mechanical model of the system. For example, as was pointed out by Maimonides, a Jewish scholar of the 12th century who worked in Spain and Cairo, the equant point for Saturn fell right on the spheres for Mercury. This was clearly awkward from a mechanical point of view. Furthermore, the equant violated the philosophical notion that heavenly bodies should be moved by a system of perfect circles, each of which rotated with uniform angular velocity about its center. To some purists even Ptolemy's eccentric deferents, which moved the earth away from the center of things, were philosophically unsatisfactory.

The Islamic astronomers adopted the Ptolemaic-Aristotelian cosmology, but eventually criticism emerged. One of the first critics was Ibn al-Haytham (Alhazen), a leading physicist of 11th-century Cairo. In his Doubts on Ptolemy he complained that the equant failed to satisfy the requirement of uniform circular motion, and he went so far as to declare the planetary models of the Almagest false.

Only one of Ibn al-Haytham's astronomical works, a book called On the Configuration of the World, penetrated into Latin Europe in the Middle Ages. In it he attempted to discover the physical reality underlying Ptolemy's mathematical models. Conceiving of the heavens in terms of concentric spheres and shells, he tried to assign a single spherical body to each of the Almagest's simple motions. The work was translated into Castilian in the court of Alfonso the Wise, and early in the 14th century from Castilian into Latin. Either this version or a Latin translation of one of Ibn al-Haytham's popularizers had a major influence in early Renaissance Europe. The concept of separate celestial spheres for each

component of Ptolemy's planetary motions gained wide currency through a textbook, Theorica novae planetarum, written by the Viennese Georg Peurbach in about 1454.

Meanwhile, in the 12th century in the western Islamic region of Andalusia, the astronomer and philosopher Ibn Rushd (Averroes) gradually developed a somewhat more extreme criticism of Ptolemy. "To assert the existence of an eccentric sphere or an epicyclic sphere is contrary to nature...," he wrote. "The astronomy of our time offers no truth, but only agrees with the calculations and not with what exists." Averroes rejected Ptolemy's eccentric deferents and argued for a strictly concentric model of the universe.

An Andalusian comtemporary, Abu Ishaq al-Bitruji, actually tried to formulate such a strictly geocentric model. The results were disastrous. For example, in al-Bitruji's system Saturn could on occasion deviate from the ecliptic by as much as 26 degrees (instead of the required three degrees). As for the observed motions that led Ptolemy to propose the equant, they were completely ignored. In the words of one modern commentator, al-Bitruji "heaps chaos on confusion." Nevertheless, early in the 13th century his work was translated into Latin under the name Alpetragius, and from about 1230 on his ideas were widely discussed throughout Europe. Even Copernicus cited his order of the planets, which placed Venus beyond the sun.

At the other end of the Islamic world a fresh critique of the Ptolemaic mechanisms was undertaken in the 13th century by Nasir al-Din al-Tusi. One of the most prolific Islamic polymaths, with 150 known treatises and letters to his credit, al-Tusi also constructed a major observatory at Maragha (the present-day Maragheh in Iran).

Al-Tusi found the equant particularly dissatisfactory. In his Tadhkira ("Memorandum") he replaced it by adding two more small epicycles to the model of each planet's orbit. Through this ingenious device al-Tusi was able to achieve his goal of generating the nonuniform motions of the planets by combinations of uniformly rotating circles. The centers of the deferents, however, were still displaced from the earth. Two other astronomers at the Maragha observatory, Mu'ayyad al-Din al-'Urdi and Qutb al-Din al-Shirazi, offered an alternative arrangement, but this system too retained the philosophically objectionable eccentricity.

Finally a completely concentric rearrangement of the planetary mechanisms was achieved by Ibn al-Shatir, who worked in Damascus in about 1350. By using a scheme related to that of al-Tusi, Ibn al-Shatir succeeded in eliminating not only the equant but also certain other objectionable circles from Ptolemy's constructions. He thereby cleared the way for a perfectly nested and mechanically acceptable set of celestial spheres. (He described his work thus: "I found that the most distinguished of the later astronomers had adduced indisputable doubts concerning the well-known astronomy of the spheres according to Ptolemy. I therefore asked Almighty God to give me inspiration and help me to invent models that would achieve what was required, and God--may He be praised and exalted--did enable me to devise universal models for the planetary motions in longitude and latitude and all other observable features of their motions, models that were free from the doubts surrounding previous ones.") Yet Ibn al-Shatir's solution, along with the work of the Maragha astronomers, remained generally unknown in medieval Europe.

<u>Influence on Copernicus?</u>

Ibn al-Shatir's forgotten model was rediscovered in the late 1950's by E. S. Kennedy and his students at the American University of Beirut. The discovery raised an intriguing question. It was quickly recognized that the Ibn al-Shatir and Maragha inventions were the same type of mechanism used by Copernicus a few centuries later to eliminate the equant and to generate the intricate changes in the position of the earth's orbit. Copernicus, of course, adopted a heliocentric arrangement, but the problem of accounting for the slow but regular changes in a planet's orbital speed remained exactly the same. Since Copernicus agreed with the philosophical objections to the equant--like some of his Islamic predecessors, he apparently believed celestial motions were driven by physical, crystalline spheres--he too sought to replace Ptolemy's device. In a preliminary work, the Commentariolus, he employed an arrangement equivalent to Ibn al-Shatir's. Later, in De revolutionibus, he reverted to the use of eccentric orbits, adopting a model that was the sun-centered equivalent of the one developed at Maragha.

Could Copernicus have been influenced by the Maragha astronomers or by Ibn al-Shatir? No Latin translation has been found of any of their works or indeed of any work describing their models. It is conceivable that Copernicus saw an Arabic manuscript while he was studying in Italy (from 1496 to 1503) and had it translated, but this seems highly improbable. A Greek translation of some of the

al-Tusi material is known to have reached Rome in the 15th century (many Greek manuscripts were carried west after the fall of Constantinople in 1453), but there is no evidence that Copernicus ever saw it.

Scholars are currently divided over whether Copernicus got his method for replacing the equant by some unknown route from the Islamic world or whether he found it on his own. I personally believe he could have invented the method independently.

Nevertheless, the whole idea of criticizing Ptolemy and eliminating the equant is part of the climate of opinion inherited by the Latin West from Islam. The Islamic astronomers would probably have been astonished and even horrified by the revolution started by Copernicus. Yet his motives were not completely different from theirs. In eliminating the equant, and even in placing the planets in orbit around the sun, Copernicus was in part trying to formulate a mechanically functional system, one that offered not only a mathematical representation but also a physical explanation of planetary motions. In a profound sense he was simply working out the implications of an astronomy founded by Ptolemy but transformed by the Islamic astronomers. Today that heritage belongs to the entire world of science.